

Intrinsic Plasma Rotation Determined by Neoclassical Toroidal Plasma Viscosity in Tokamaks

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Intrinsic steady state plasma rotation is important for plasma confinement in ITER, since the momentum input is expected to be small. There has been many observations about it in present tokamaks, and an experimental scaling has been obtained in [1]. However, the underlying physics is not clear yet.

It is well known that the intrinsic plasma rotation in stellarator is determined by non-ambipolar diffusion due to 3D helical ripple [2]. Tokamak is an axisymmetric toroidal device. The toroidal asymmetry in it was often neglected in the past. However, 3D effects in tokamaks have been paid more and more attention in recent researches, because intrinsic error field cannot be avoided, there are MagnetoHydroDynamics (MHD) perturbations in the plasma, and furthermore, Resonant Magnetic Perturbation (RMP) is frequently used to control Edge Localized Mode (ELM) and Resistive Wall Mode (RWM) in present tokamaks and may also be used in future ITER.

The non-ambipolar diffusion due to small 3D magnetic perturbation described by the Neoclassical Toroidal plasma Viscosity (NTV) theory [3] may be important in determining the intrinsic plasma rotation in tokamaks. The NTV theory in different collisionality regimes has been well developed in the last few years, and it has been summarized in [4]. The numerical results showed a good agreement with the analytic solutions in different asymptotic limits [5]. The flux of the trapped electron was found to be important in low collisionality case [6].

Recent result on DIII-D indicated that the counter-current steady state flow driven by the RMP consisted with the NTV theory [7]. The observation on JET also showed that the intrinsic rotation strongly depended on the toroidal field ripple, which might also be linked to the NTV effect [8].

The intrinsic toroidal plasma rotation determined by the NTV effect in tokamaks is investigated in this paper.

The intrinsic rotation due to NTV can be found by searching the root of the ambipolarity constraint $\Gamma_i(\Omega_\phi) - \Gamma_e(\Omega_\phi) = 0$, where Ω_ϕ is the toroidal rotation and Γ_i and Γ_e are the ion and electron particle fluxes, respectively. The collisionality and rotation dependencies of ion and electron fluxes are evaluated from the numerical modeling developed in [5].

From the flux-force relation [9], it has $T_{NTV} = T_{NTV,i} + T_{NTV,e} \propto \Gamma_i - \Gamma_e$. It means that the ambipolarity constraint is equivalent to that the total NTV torque equals 0.

The parameters used in the modeling are: $R_0 = 3.0\text{m}$, $\rho \equiv \sqrt{\Psi_T/(\pi B_0)} = 0.2\text{m}$, where Ψ_t is the toroidal magnetic flux, $B_0=2\text{T}$ is the magnetic field strength on the magnetic axis, $M_i/M_p = 2$, $m/n = 1/1$ is the poloidal/toroidal mode number of the magnetic perturbation, $q = 1.1$, $b_{1/1} = 0.2\%$, plasma density $N \in [0.1, 1](10^{20}\text{m}^{-3})$, $T_i = T_e = P_0/N$, $P_0 = 1.8 \times 1(\text{keV}) \times 10^{20}(\text{m}^{-3})$, $L_N = N/d_\rho N = L_T = T/d_\rho T = 1\text{m}$, toroidal rotation $\omega_\phi \in [-300, 300](\text{krad/s})$.

The rotation dependence of the ion (blue circles) and total (red triangles) NTV torque density for different collisionalities, $\nu_{*i} \equiv \frac{\nu_i}{2\epsilon}/(\epsilon^{1/2}\omega_{ti})=0.7, 0.011, 0.0007$, where ν_i is ion collisionality, $\epsilon \approx \rho/R_0$ and ω_{ti} is the ion transit frequency, are shown in Fig. 1 (a-c). For high collisionality case (a), the ion NTV is dominant and there is only one root in the counter-current direction. It corresponds to the 'ion root' named in stellarators. For low collisionality cases (b and c), the electron NTV is also important and there are three roots. Two of them are stable roots. One corresponds to the 'ion root' in the counter-current. The second stable one corresponds to the 'electron root' in co-current direction, near which the electron flux is dominant. The third one is an unstable root. The NTV torque drives the plasma rotation towards one of the stable roots. This means that the intrinsic toroidal rotation in low collisionality case can also be possible in co-current direction.

The collisionality dependence of the found roots is shown in Fig. 2. The circles are the ion roots, the stars are the electron root, and the triangles are the unstable roots. The corresponding normalized roots are shown in Fig. 3. The roots are normalized to $\omega_{*Ti} \equiv \frac{qd_\rho T_i}{\rho B_0}$. It shows that magnitude of these two stable roots is around $(2-3)|\omega_{*Ti}|$. They scale like $|\omega_{*T}| \propto |\frac{\rho d_\rho T}{R_0 I_p}|$, where I_p is the plasma current. This is also similar to the experimental scaling [1].

In summary, the intrinsic toroidal rotation due to NTV effect in tokamaks is investigated. The NTV can drive a flow with a magnitude of the diamagnetic frequency. It is in counter-current direction for high collisionality case, while it can be both co-current and counter-current directions for low collisionality case. The prediction of intrinsic rotation due to NTV on ITER will also be discussed.

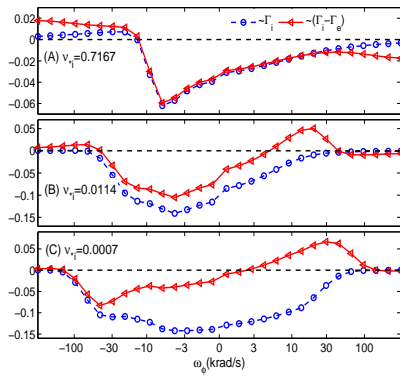


Figure 1: The ion and total NTV torque densities for different collisionalities.

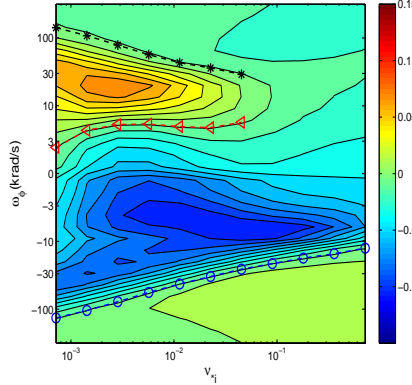


Figure 2: The collisionality dependence of the found roots for $\Gamma_i - \Gamma_e = 0$.

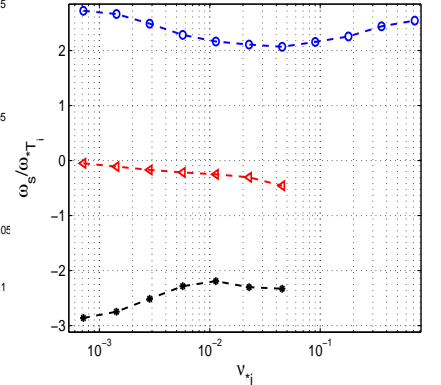


Figure 3: The collisionality dependence of the normalized roots.

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Abstract: Intrinsic steady state plasma rotation is important for plasma confinement in ITER, since the momentum input is expected to be small. It is well known that the intrinsic plasma rotation in stellarator is determined by non-ambipolar diffusion due to helical ripple [1]. The non-ambipolar diffusion due to small 3D magnetic perturbation described by the Neoclassical Toroidal plasma Viscosity (NTV) theory [2] may be important in determining the intrinsic plasma rotation in tokamaks, because intrinsic error field cannot be avoided, and furthermore, resonant magnetic perturbation is frequently used to control Edge Localized Mode and Resistive Wall Mode. The NTV theory in different collisionality regimes has been well developed in the last few years, and it has been summarized in [3]. The numerical results showed a good agreement with the analytic solutions in different asymptotic limits [4]. The flux of the trapped electron was found to be important in low collisionality case [5].

The intrinsic toroidal plasma rotation determined by the NTV effect in tokamaks is investigated in this paper. It is found by searching the root of the ambipolarity constraint $\Gamma_i(\Omega_\phi) - \Gamma_e(\Omega_\phi) = 0$, where Ω_ϕ is the toroidal rotation and Γ_i and Γ_e are the ion and electron particle fluxes, respectively. The ion and electron fluxes are evaluated from the numerical modeling developed in [4].

It is found that the result strongly depends on the plasma collisionality. For high collisionality case, the ion flux is dominant and the intrinsic steady state flow is in counter-current direction. It corresponds to the 'ion root' named in stellarators. For low collisionality case, there are three roots. Two of them are stable roots. One corresponds to the 'ion root' in the counter-current. The second stable one corresponds to the 'electron root' in co-current direction, near which the electron flux is dominant. The third one is an unstable root. The NTV torque drives the plasma rotation towards one of the stable roots. This means that the intrinsic toroidal rotation in low collisionality case can also be possible in co-current direction.

Both of these two roots scale like $|\omega_{*T}| \equiv |\frac{qd_\rho T}{\rho B_0}| \propto |\frac{\rho d_\rho T}{R_0 I_p}|$, where q is the safety factor, T is temperature, $\rho \equiv \sqrt{\Psi_T/(\pi B_0)}$ reduces to minor radius in cylindrical coordinate, Ψ_t is the toroidal magnetic flux, B_0 is the magnetic field strength on the magnetic axis, and I_p is the plasma current. The prediction of intrinsic rotation due to NTV on ITER will also be discussed.

References

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